

## The design of IPT system for multiple kitchen appliances using class E LCCL circuit

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### ABSTRACT

Since many years ago, kitchen appliances are powered up by cable connected. This create a troublesome case as wire might tangle together and cause kitchen table messy. Due to this, wireless power technology (WPT) is introduced as its ability is to transmit power to load without physical contact. This leads to cordless solution better in safety as the product can be completely seal, highly expandable power range. This work focuses on the design of WPT based on inductive approach to power up multiple kitchen appliances. The selection of inductive approach over its partners capacitive and acoustic is mainly due to high power efficiency. Class E inverter is proposed here to convert the DC to AC current to drive the inductive link. A 1 MHz operating frequency is used. To ensure the circuit is robust with load variations, an LCCL impedance matching is proposed. This solution is able to maintain the output power if there is a slight change in load impedance. Finally, the developed prototype is able to supply 50V utput which can achieve power transmission up to 81.76%.

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## 1. INTRODUCTION

Nowadays, wireless power transfer (WPT) technology has become one of the top research areas for reliable applications, especially in low-power technology applications such as cell phone chargers, smart card systems, radio frequency identification (RFID), high-power electric vehicles (EV) and biomedical equipments [1-5]. WPT transfers power or energy from the power source to the power load through the medium without a connection line (physical contact) [1-3]. The WPT system will eliminate existing high-voltage transmission cables, towers and substations between power stations and consumers, as well as facilities interconnected by electrical technology plants worldwide [6]. WPT's advantages in cable elimination and maintenance-free operation are particularly helpful in kitchen applications to put aside the electronic kitchen appliances we use every day.

One of the popular WPT technology is based on capacitive coupling between transmitter and receiver. However, existence capacitor required high withstanding voltage along with the high capacitance value for a given output current which means that this kind of supply is only practical for high power applications [7, 8]. On the other hand, acoustic power transfer is comparatively new technology which optimizing sound waves vibration or ultrasonic propagate waves to convey energy wireless for power transmission. Although it is a light-based system but still able to supply a large amount of power. Unfortunately, its diffraction loss directly affects efficiency over far distance [9-11].

Due to the above mentioned issue, this work focuses on the inductive approach in order to transmit power to the multiple kitchen appliances. The method is also known as Inductive Power Transfer (IPT). IPT system offers several advantages, such as; 1. Ability of transmitting high-power transmission, 2. Can handle robustness load which mean mobility of multiple kitchen utensils shift around the table [12-14]. Although the IPT could overcome power transmission and distance limitation but still the hardships of large acoustic mismatch of the transmitter and receiver with the medium could lead to a severe limit on the efficiency of power transfer. Hence, the inductive approach is preferable in this work.

Currently, in the commercial market induction cooker using direct induction heating of cooking vessels, rather than relying on indirect radiation, convection, or thermal conduction. Induction cooking allows high power and very rapid increases in temperature to be achieved, and changes in heat settings are instantaneous [15]. However, induction cooker only has limited two slots and mainly for cooking. Also, induction cooker could not be shifted from one location to another location easily. By utilizing IPT system, the power can be transferred to multiple kitchen appliances and enable to power up not only cooker but also boiler, fruit blender, mixer and others. Besides that, the kitchen load is shiftable around the kitchen table and this increases the flexibility on preparing food. Therefore, in this work wireless multiple kitchen appliances system is proposed using inductive approach.

## 2. OVERVIEW OF THE PROPOSED IPT METHOD

Figure 1 shows the proposed IPT system for this work. This prototype is designed to deliver high power (at least 50W) with the supply voltage up to 50V and effective distance gap is 5cm. Mosfet driver is used to supply 5V voltage to drive Mosfet in Class E Inverter circuit. IRFP250N Mosfet is used here as its able to switch at 1 MHz frequency with 50% of duty cycle. High frequency switching allows power to be transferred in a short duration [16].

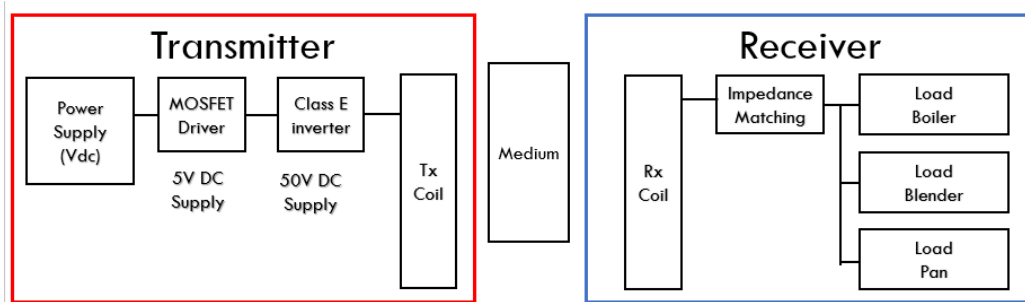


Figure 1. IPT system block diagram

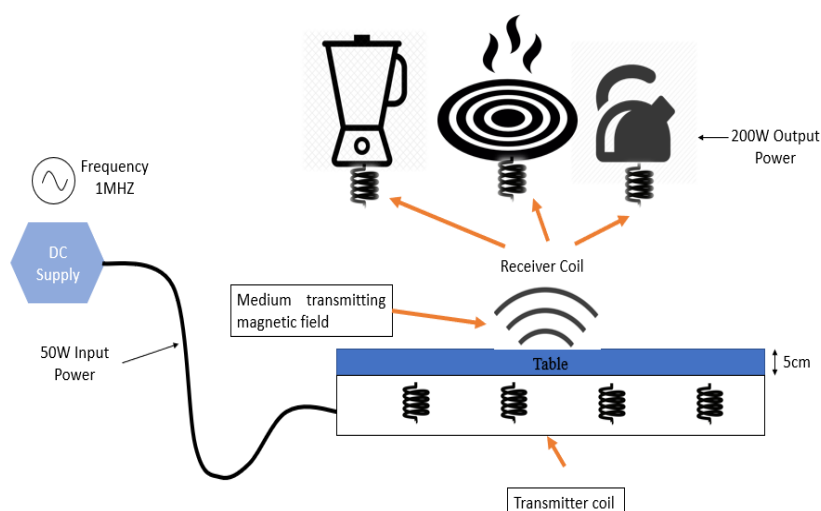


Figure 2. General overview of the project

In IPT system, a high frequency current is desired to drive the magnetic field coupler so that the magnetic flux can flow through it to provide the load with the required power. Therefore, a Class-E inverter is designed as the high frequency inverter [17, 18] at the transmitter to convert DC source to AC. On the other hand, the problem of power loss during the transmission process is overcome by proposing LCCL impedance matching circuits at the receiver part. The overall illustration of the work is shown in Figure 2.

### 3. METHODOLOGY

The basic conceptual design of this prototype is shown in Figure 1 and Figure 2 respectively.

### 3.1. Class e inverter design

Class E Inverter is a well-known circuit implemented for high frequency applications [19]. The circuit has low switching losses with high frequency output which benefits to our proposed system. Basically, class E inverter is categorized as class E zero voltage switching (ZVS) inverter and the class E zero current switching (ZCS) inverter. The class E inverter circuit is shown in Figure 3.

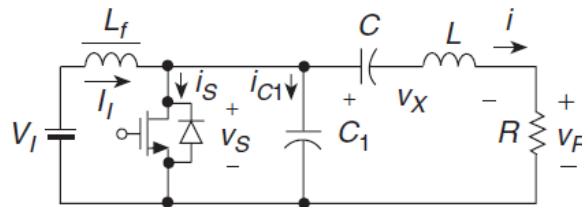


Figure 3. Class E circuit

The circuit consists of power MOSFET operating as a switch, L-C-R series-resonant circuit, shunt capacitor C1, and choke inductor Lf. The switch turns on and off at the operating frequency,  $f = \omega/2\pi$  which determined by a driver. Besides the low input of the MOSFET gate, Vg, as the voltage drain, Vd should be three times greater than Vg to ensure the resonance tank not be burned. The resistor R is an ac load. The choke inductance Lf is assumed to be high enough so that the ac current ripple on the dc supply current I1 can be neglected. A small inductance with a large current ripple is also possible [20]. When the switch is ON, the resonant circuit consists of L, C, and R because the capacitance C1 is short-circuited by the switch. However, when the switch is OFF, the resonant circuit consists of C1, L, C, and R connected in series. Because C1 and C are connected in series, the equivalent capacitance is lower than C and C1. In the resonant tank circuit, there is an inductor series with capacitor then parallel with a capacitor. The value of the passive elements is decided according to the following equations:

The load resistance, R can be calculated as,

$$R = \frac{8}{\pi^2 + 4} \times \frac{VI}{P_0} \quad (1)$$

then, based on the proposed operating frequency, shunt capacitor, C1 and choke inductor, Lf can be calculated as follows [8]:

$$C_1 = \frac{8}{\pi(\pi^2+4)\omega R} \quad (2)$$

$$L_f = 2 \left( \frac{\pi^2}{4} + 1 \right) \frac{R}{f} \quad (3)$$

the series capacitance,  $C$  and series resonant inductor,  $L$  are given as:

$$C = \frac{1}{\omega R \left( Q_L - \frac{\pi(\pi^2 - 4)}{16} \right)} \quad (4)$$

$$L = \frac{Q_{LR}}{w} \quad (5)$$

Note that,  $Q$  is a Quality Factor that needs to be determined first. In this work,  $Q$  is 10. This value is chosen so that the bandwidth obtained is sufficient enough for tuning purpose later to guarantee the ZVS condition of the circuit, see [10] for details.

### 3.2. Impedance matching circuit

Implementation of impedance matching is applied at receiver side in order to improve power efficiency [21, 22]. A 1 MHz class E inverter circuit is implemented with series LC impedance matching at transmitter part [23]. Parallel topology CL part of impedance matching connected with the load in parallel topology is proposed at receiver side, so the resonant behavior will compensate the power being transfer [24]. This impedance matching circuit is known as LCCL topology [25], see Figure 4 for the schematic of the circuit. Based on simulation work, the perfect coupling factor is 0.2 with an effective distance gap of 5 cm.

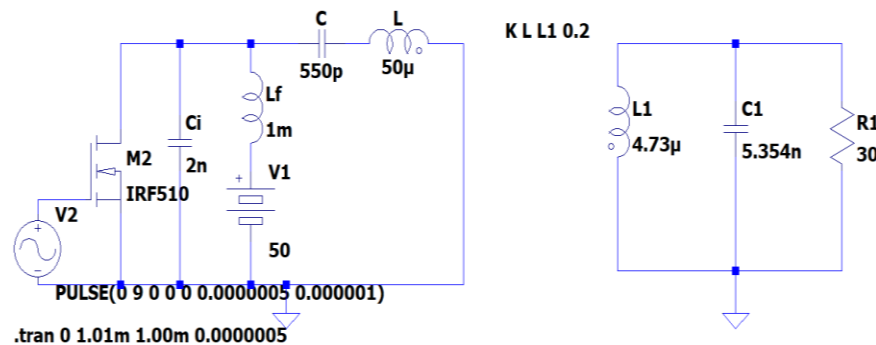


Figure 4. Schematic for LCCL impedance matching circuit

### 3.2. Experimental work

The transmitter circuit is designed on the PCB board then connect to the transmitter inductance coil. The transmitter circuit included class E inverter circuit with series LC of impedance matching. Receiver module are built into the load which underneath the boiler with sealed. The receiver circuit included receiver inductance coil connected to the parallel topology of CL impedance matching. Figure 5 and Figure 6 illustrates the experiment set up of the proposed system.

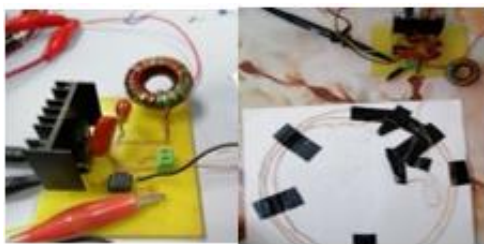


Figure 5. Transmitter side

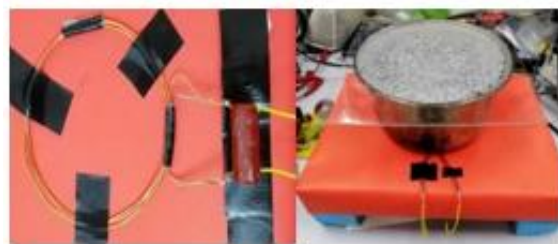


Figure 6. Receiver side

## 4. RESULTS AND DISCUSSION

Based on the desired output of class E inverter circuit, the value of components in resonant circuit is decided using the equation from (1) to (5) by using the values that are given in Table 1. All the calculated values are then tabulated in Table 2. In this class E inverter circuit, IRFP250N MOSFET is chosen because its low static Drain-to-Source On-Resistance,  $R_{DS}$  and withstand high power dissipation,  $P_D$ . Function generator generates square wave pulse and MOSFET driver is used to boost the square wave pulse to achieve minimum voltage required by the MOSFET. In addition, ZVS condition has to be considered to produce high power efficiency in class E circuit. Basically, the component values in the resonant circuit must be selected appropriately so that the switch will turn on at zero voltage.

Table 1. Design specification for class E inverter circuit

Design Specification	Value
Rated power, $P_{out}$	50W
Input voltage, $V_i$	50V
Duty cycle, $D$	50%
Frequency, $f$	1MHz
Quality factor	10

Table 2. Class E inverter parameter

Design Specification	Value
Choke Inductor, $R_f$	1mH
Shunt Capacitor, $C_{shunt}$	2nF
Series Capacitor, $C_{tank}$	550pF
Series inductance, $L_{tank}$	50μH
$R_{load}$	30Ω

Figure 7 displays the gate voltage and drain voltage which fulfilled ZVS condition of the simulation work. When the VG drops to zero the VD achieves 170V. This happens when MOSFET acts as open circuit. This definitely fulfills the characteristics of class E inverter itself which produces VD 3 times larger than the input voltage. Meanwhile, Figure 8 provides results for experimental work of class E inverter circuit. From the experimental results, 50V dc supply and 1MHz resonant frequency the output ZVS waveform has been successfully achieved (with some distortion) and this is shown in Figure 8(a). For Figure 8(b), the green line is the output voltage at the load. The output from this output voltage will be then connected to the transmission coil.

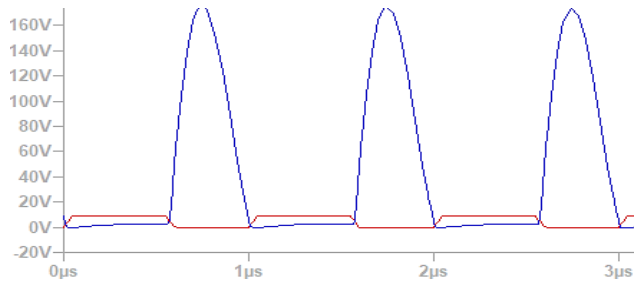


Figure 7. ZVS condition in class E circuit

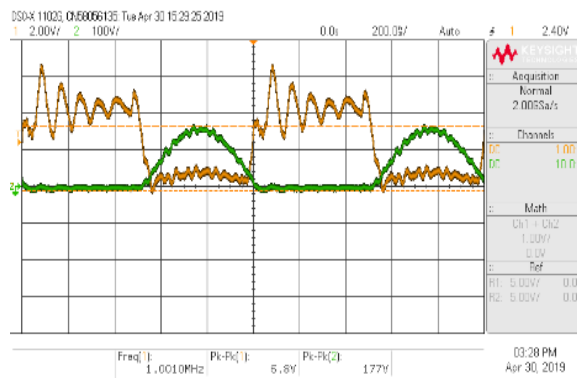


Figure 8(a). ZVS from oscilloscope

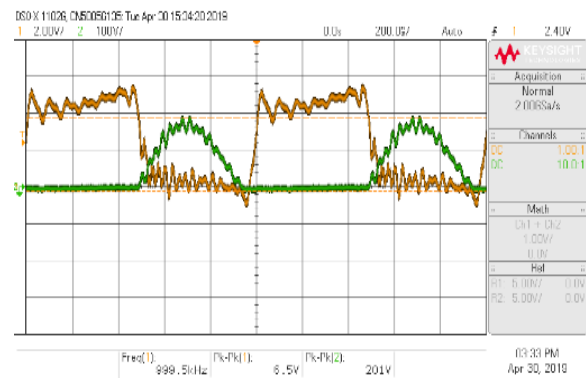


Figure 8(b). Drain voltage versus output voltage at load

#### 4.2. Analysis of impedance matching

Independent class E circuit provides input power of 35.57W and output power of 30.845W. The power efficiency here is 86.71%. By proposing LCCL impedance matching circuit, the input power increases to 121.19W and output power is 109.16W. The power efficiency is 90%. In this system, kitchen

appliances require high power to power up, hence impedance matching plays an important role to boost up the efficiency, so the output power. This is highlighted in Figures 9 and 10 correspondingly.

For the analysis purpose, we would like to study the impact of coupling variation to the circuit with and without impedance matching circuit. In this context the following parameters are made constant; At transmitter side:  $C_{\text{shunt}} = 2\text{nF}$ , choke inductor =  $1\text{mH}$ ,  $C_{\text{tank}} = 550\text{pF}$ ,  $L_{\text{tank}} = 50\mu\text{F}$ , and input voltage =  $50\text{V}$ . At receiver side,  $L_1 = 4.73\mu\text{F}$  and  $C_1 = 5.354\text{nF}$  and load =  $300\Omega$ . The manipulated variable is coupling factor is varied from 0 – 1. The responding variable is output power. We can see that the output power achieved the highest one with impedance matching circuit at 0.2 coupling factor. Meanwhile, highest output power without impedance matching happened at 0.4. Based on this it is obvious to us that applying impedance matching circuit allow one to transfer power at higher distance than without impedance matching circuit. Figure 11 explains this scenario where output power without impedance matching have shifted to right and achieved the same power at a nearer distance.

Figures 12-14 provides details results on the reason of coupling factor 0.2 gives the highest power output. It is obvious from Figure 13 that at 0.2 coupling factor, the ZVS is successfully achieved and leads to approximately switching loss. This will greatly increase the efficiency of such system. The overall comparison between the performance of the circuit with and without impedance matching with the variation of coupling factor is shown in Figure 15.

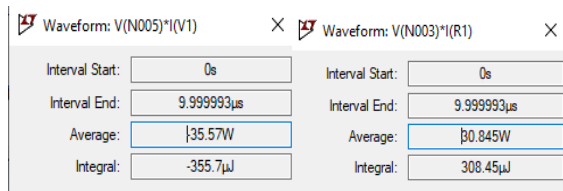


Figure 9. Class E circuit without impedance matching

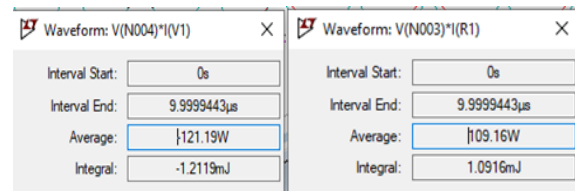


Figure 10. Class E circuit with impedance matching

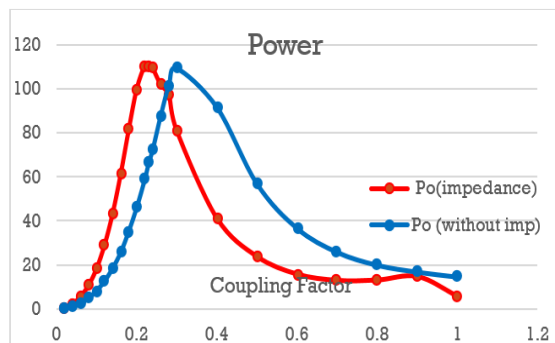


Figure 11. Power versus coupling factor

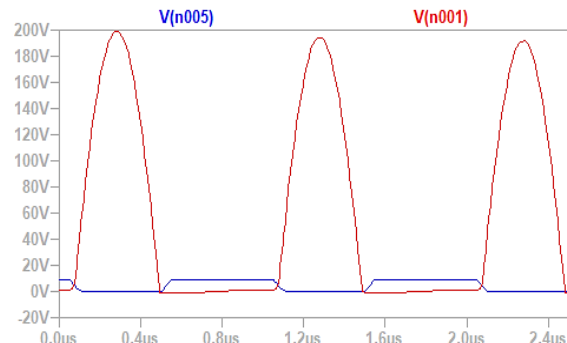


Figure 12. ZVS condition at coupling factor of 0.1

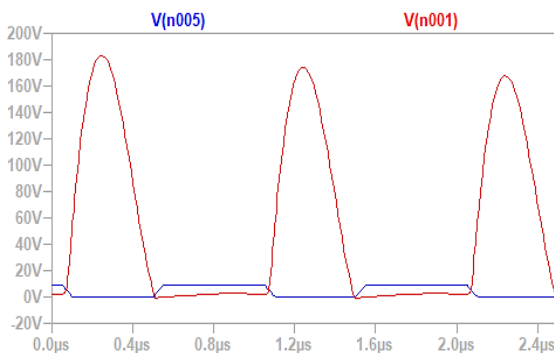


Figure 13. ZVS condition at coupling factor of 0.2

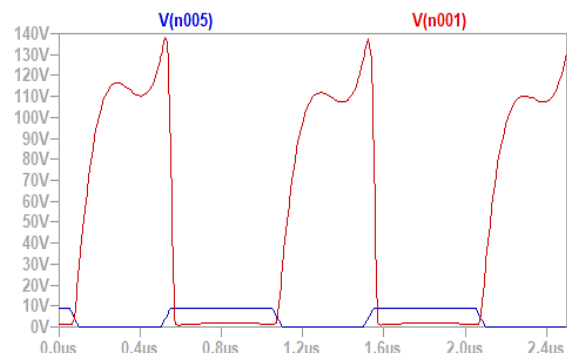


Figure 14. ZVS condition at coupling factor of 0.3



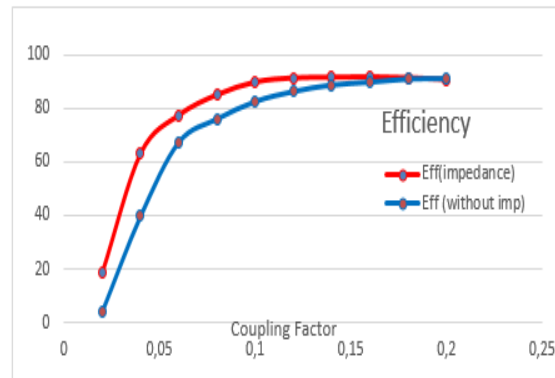


Figure 15. Power efficiency versus coupling factor with and without impedance matching

### 4.3. Prototype development

The prototype of the work is shown in Figure 16. Three loads are used here, namely, LED light, stove and fruits blender. The proposed IPT system is able to power up loads successfully. In this context, the kitchen light was lighted up, the fruit blender is spinned and the boiler has boiled during power transmission. By supplying 50VDC to the transmitter part, the class E inverter converts DC source to AC source. This is achievable by locating the receiver part at the effective area. The system able to deliver 72W output power to power up the kitchen appliances with 81.76% of power efficiency

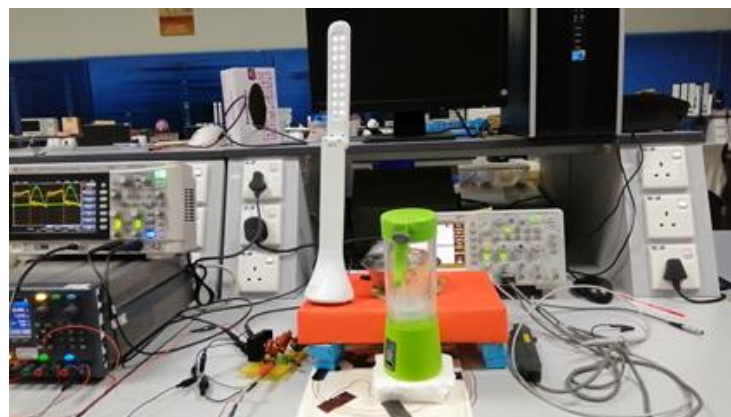


Figure 16. Complete prototype of the proposed method

## 5. CONCLUSION

In conclusion, the project had achieved the objectives of designing and developing the high efficiency resonant class E inverter circuit. The class E inverter circuit is successfully constructed in simulation and implemented in practical. The efficiency achieved for simulation is 90.07% while experimental result achieved 81.76%. Additionally, the objective on designing impedance matching circuit by using parallel configuration topology had improved the power efficiency of the system from 86.71% to 90% for a gap distance of 5cm. The future works are; 1. The safety module at the receiver side has to be designed so that load can be protected 2. The auto tuning circuit needs to be introduced to ensure the effectiveness of the proposed system although at misalignment condition.

## ACKNOWLEDGEMENTS

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